I am sailing (stormy waters)**, I am flying** (passing high clouds)
The Symmetry of Wings and Sails.

***All of the principal items of flight performance involve steady flight conditions and equilibrium of the airplane* [1]. The same is true for the performance of boards and boats when sailing and foiling.**

A comparison of most basic parameters between aircrafts and sailcrafts reveals similarities in the understanding of the principal physical laws as well as variations and differences in their application to create a balance of forces when dealing with weight, lift, drag and driving forces (propulsion).

1. Subject of discussion

The most basic principles and parameters of the design and operation of aircraft and sailcraft include the understanding and calculation of the

- Driving forces or propulsion;
- Lift and drag forces;
- Range of operation
  (angle of attack α against the wind);
- Flow and pressure fields around wings or sails;
- Balance of forces in two- and three-dimensional media (air or water);

and the parameters to increase lift a.o.

2. Driving force / propulsion

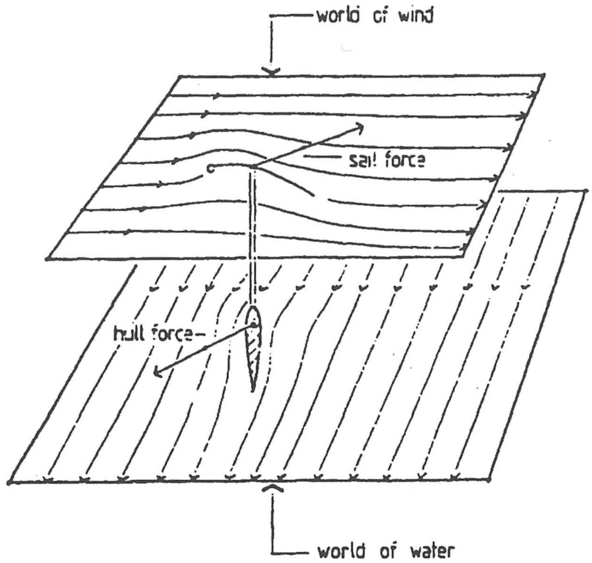
Aircrafts are usually propelled by (jet) engines, while gliders use the longitudinal component of the weight as their driving force (see paragraph 5).

The movement of the aircraft creates a relative wind and the wings create lift by the deflection of this airstream. This basic equilibrium of lift and weight (together with thrust and drag) can be described in the two dimensions x and z.

aircraft	sailcraft
thrust* from power plant	lift / drag from wind on sails and from water on hull and keel (see glossary)

* for gliders: longitudinal component of weight

The sailcraft's driving forces are lift and drag from natural winds in combination with the equivalent forces on hull and keel in the water. They prevent the boat from being "blown away" and allow a three-dimensional equilibrium of forces. The apparent wind on a sailcraft will be experienced from a remarkably different angle than the true wind (see paragraph 6, Fig. 17). Note that *true*, *relative* and *apparent* wind are synonymous terms.



The movement of two fluid media with respect to one another is exploited by sailing craft which, by transferring momentum from the air to the water, are able to propel themselves through the water (and the air).

Fig. 1 The basic principle of sailing [2].

Speed

Possible speeds of artificially propelled aircrafts are much greater than of naturally propelled sailcrafts (see Fig. 13 for aircraft and Fig. 17 for sailcraft; Note that speed vectors are to scale 1:10 and 1:2).

However, speeds achievable by sailcrafts are clearly greater than the true wind speed, e.g. for kiteboards or the America's Cup boats from 2013 and 2017 (foiling catamarans). Sailing records for sailcraft on solid ground proof speeds up to four times the true wind speed (low drag on ice, sand or salt sea).

3. Balance of forces

The basic descriptions of the balance of forces in vertical and horizontal directions are:

aircraft	sailcraft
weight equals lift	weight equals buoyancy / hydrodynamic lift when foiling or planning
thrust equals drag	sail driving force (lift/drag) equals hull drag force
	heeling force (part of lift f.) equals hull lift force

See paragraphs 5 and 6 for more details.

Creating and calculating of lift and drag

The most basic principle of flying and sailing are wings or sails moving through air and *creating lift by the deflection of an airstream* [1], no matter what materials or construction details are used. Drag is an inevitable consequence of this. For boards, hydrofoils and keels, it is the deflection of a water stream (current) generating lift (and drag).

Lift force $F_{Lift} = \frac{1}{2} \cdot C_L \cdot \rho \cdot A \cdot v^2$ [N]

Drag force $F_{Drag} = \frac{1}{2} \cdot C_D \cdot \rho \cdot A \cdot v^2$ [N]

Lift Coefficient C_L : function of camber, flow field and a.o.a.
Drag Coefficient C_D : function of camber, flow field and a.o.a.
Area A [m^2] apparent speed v [m/s]
ρ : density of the fluid, function of altitude and depth [kg/m^3]

The equations for lift and drag forces are independent of the fluid media (air or water). The coefficients of lift and drag are a function of the angle of attack (a.o.a). The camber of the wing is of great significance to this function.

4. Range of operation

Dimensions

Basically, if propulsion and structure are strong enough, an aircraft is free to head in any direction in the three-dimensional air space (x-y-z). However, basic depiction of forces is two-dimensional (x-z) and so is the movement against the wind, measured as angle of attack α (see paragraph 5).

For sailcraft, freedom of heading is only two-dimensional (x-y, on the water surface), while basic depiction of forces is three-dimendional (x-y-z) (see Fig. 1 and paragraph 6).

Angle of attack a.o.a. α

To compare freedom of heading, one may consider the two-dimensional depiction of the movement against the wind as appropriate (see Fig. 2 and paragraphs 5 and 6).

aircraft	sailcraft
~ 26 ° (-10 ° to + 16 °)	~ 2 * 70 ° = ~ 140 °

The range of a.o.a. α values to the wing / sail do not overlap, but complement each other to almost 180°.

The mounting angle or angle of incidence σ is fixed for aircraft – as well as the angle of incidence σ (mounting angle). Thus, freedom of heading for aircraft relative to the wind is identical to the range of α and therefore limited to only ~ 26 °. For flight path angles γ > a.o.a. α, additional propelling force is needed (s. p. 5, Fig. 14).

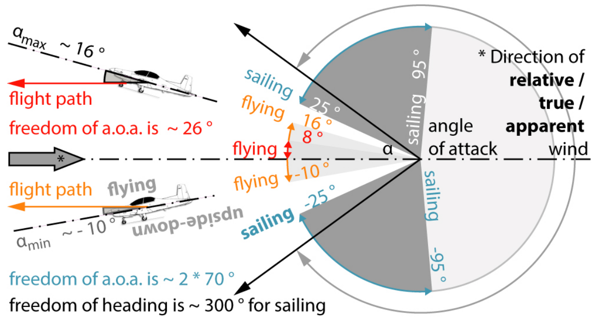


Fig. 2 A.o.a. and freedom of heading for air and sailcraft (range of values in the right scale).

Sails can be considered flexible wings with no thickness. Their flexibility in regard to the angle of incidence σ and the cambered shape creates a very wide field of operation in terms of the angle of attack α (2 * ~70 ° , see par. 6, Fig. 17) and freedom of heading (~ 300 °, thus almost a full circle).

The combination of a.o.a. α + camber is a result of easing or trimming the sail(s).

Flow field around wing / sail

An attached flow of air to the wing or sail is fundamental to produce enough lift to both bring and keep an aircraft in the air (against gravity) or to propel a sailcraft against the true wind. Attached flow on both sides of a sail (Fig. 3, state 2) is always aimed for headsails (no turbulences), except for running courses.

Aircraft	sailcraft
attached *	attached/separating/stalled

*otherwise stalled
-> no equilibrium of forces possible

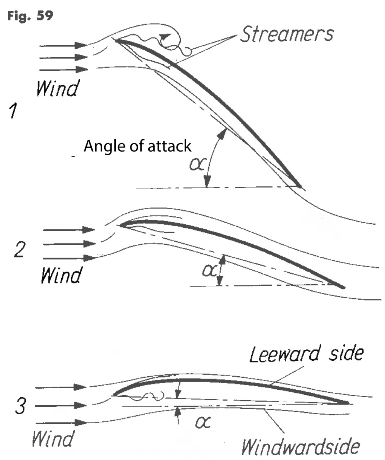


Fig. 3 Effect of angle of attack on flow of air on both sides of a foil or sail (from [3]). State 2 is always aimed at.

However, sailcraft can also be propelled by a combination of lift and drag with the wind while the airflow can be partly or completely separating on the lee-side of the sail for running courses, that is heading away from the true wind (see p. 6, Fig. 19).

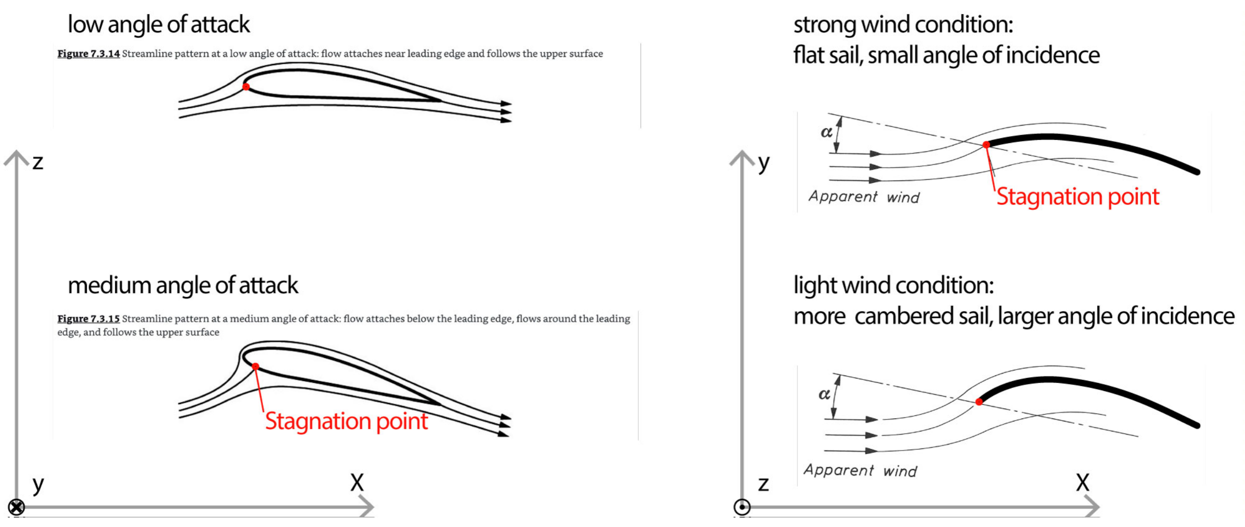


Fig. 4 a) 2-D flow fields on a) wings (x-z, from [4]) b) sails (x-y, from [5], redacted for better legibility).

Stagnation point

At the stagnation point $v_{fluid, local}$ is zero. The pressure is highest for both wings and sails (see Fig. 4):

- For aircrafts, it is located at the front of the wing and it is a function of a.o.a. and true air speed.
- For (properly trimmed) sailcraft, the stagnation point is the luff (headsail) and the mast (mainsail). The proper trimming of the sail is a function of a.o.a. and apparent wind speed. (see glossary)

Note, that there will still be a stagnation point at the luff or mast for separated flow of air.

5. Balance of forces on aircrafts

To be in equilibrium, lift, drag, thrust and weight must add up such that they can be combined into a closed run of vectors (see Fig. 5 on the right).

The calculation of the equilibrium of forces includes the flight path angle γ, the angle of attack α, the pitch angle $\theta = \gamma + \alpha$ and the angle of incidence / mounting angle σ. All components of the equations depend on each other, which means computation must be iterative. Simplification however is possible, because α and σ are small and therefore cos (small angle) is ~ 1 and sin (small angle) is ~ 0. For an engineers' depiction (to the right scale) there is

$$F_{Lift} = F_{Weight} \cdot \cos\gamma \quad [\mathrm{N}]$$

and

$$F_{Thrust} = F_{Drag} + F_{Weight} \cdot \sin\gamma \quad [\mathrm{N}]$$

The max. climb angle γ is

$$\gamma_{max.} = \sin^{-1}\left(\frac{F_{Thrust,max.} - F_{Drag}}{F_{Weight}}\right) \quad [\mathrm{deg}]$$

dependend on the available thrust.

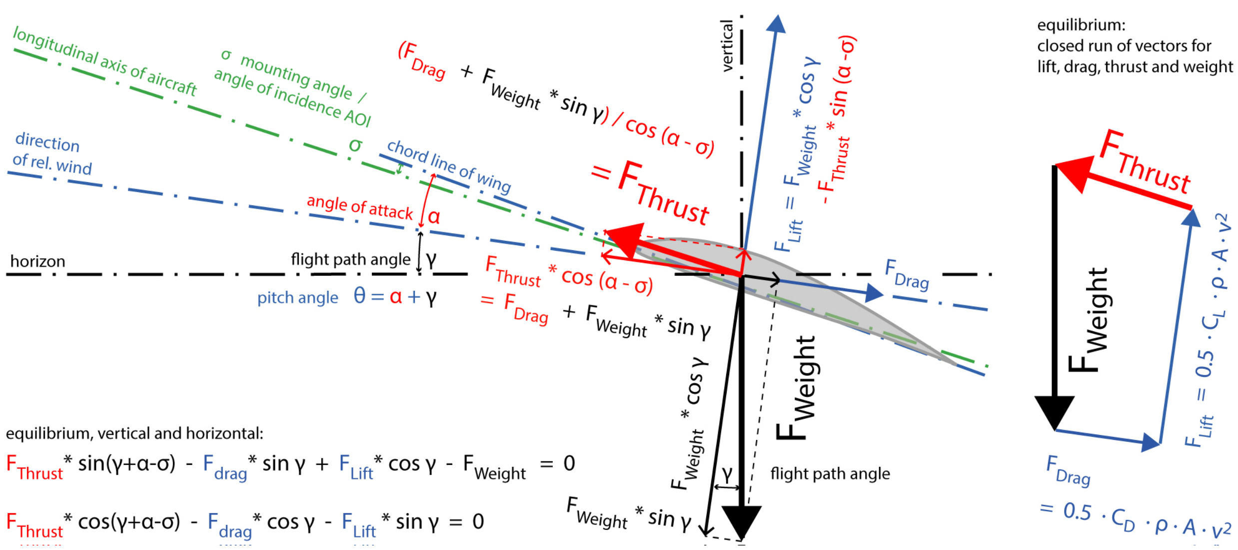


Fig. 5 2-D balance of forces on aircraft (x-z, from different references).

Range of angle of attack

The angle of attack a.o.a. needs to stay within certain limits so that the airstream stays attached to the wing on both sides and the wing therefore produces enough lift to carry the weight of the craft. These limits are only a few degrees from each other (see paragraph 4 and Fig. 6).

Fig. 6 a) Instruments showing a.o.a. b) strings used as tell-tales on a gliders cabin roof.

For symmetrical wings or foils, the absolute value of $C_{L,min}$ equals $C_{L,max}$. Thus, in terms of the a.o.a. it does not matter, if one flies head up or upside down.

For unsymmetrical foils with cambered shape on the upper side of wings or foils, there is

$$C_{L,min} \sim - C_{L,max} + 2 * C_{L,0}$$

Thus, the range of the a.o.a. values for flying upside down is smaller than the ordinary way "heads up" (see Fig. 7).

The angle of attack a.o.a. and thus drag are a function of true airspeed TAS and density of air δ or altitude (for a given aircraft, see Fig. 8 and 9).

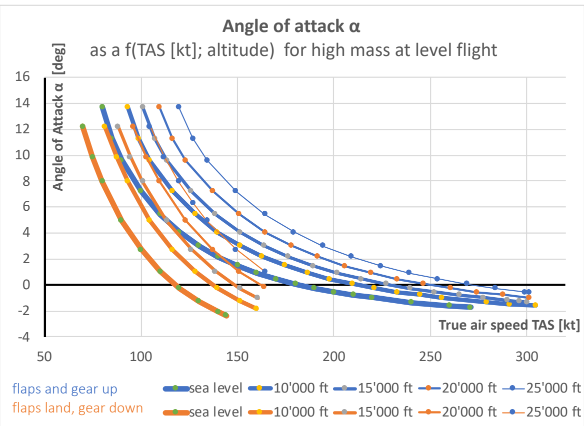
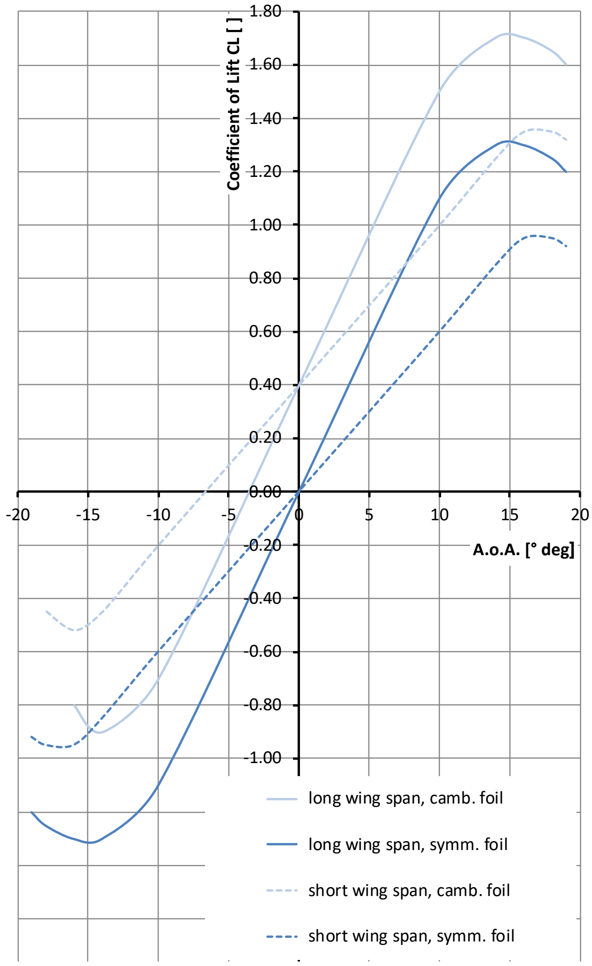


Fig. 8 Angle of attack vs. true air speed: Actual data of modern military trainer aircraft ([6]).

Vertical flight path

For aircrafts, a distinction can be made between flight route, (x-y, heading for the destination airport) and vertical flight path (x-z, take off, climb, cruise, descent, approach and landing).



Example of NACA 2415: see paragraph 14, Fig. 36

Fig. 7 Lift coefficient C_L vs. angle of attack: Typical values from different references.

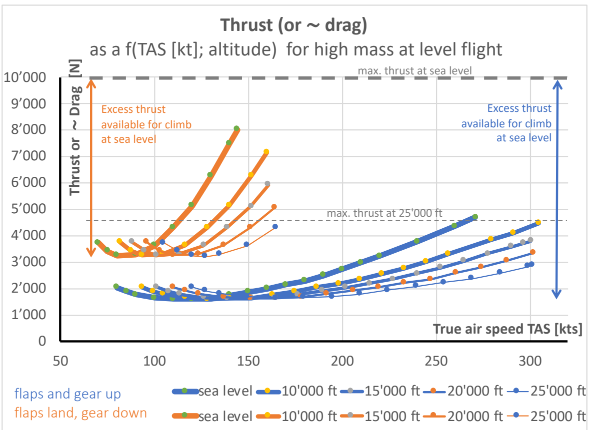


Fig. 9 Thrust (or drag) vs. true air speed: Actual data of modern military trainer aircraft ([6]).

While both of them in reality depend on wheater and wind conditions and economic considerations, the vertical flight path is suitable to show some typical states of flight operation and limit conditions: max. rates / angles of climb / descent (see Fig. 12 a / b).

Steepest vs. fastest climb

Fig. 10 shows key parameter to determine climb:

- Steepest climb means highest possible flight path angle γ, which can be found at low speed.
- Fastest climb means highest possible rate of climb, found at relatively high speed.

For both, thrust available to climb is

$$F_{Thrust,max.} - F_{Drag} = F_{Weight} \cdot \sin(\gamma_{max.}) \text{ [N]}$$

The angle of attack is high for low speeds and low for high speeds, of course.

Steepest vs. most gentle descent

Fig. 11 shows key parameter to determine descent:

- Fastest and steepest descent is determined by structural limits. The maximum operating speed (v_{MO}) is a function of altitude.
- The most gentle way of descent is by gliding (power off): $F_{Drag} = -F_{Weight} \cdot \sin\gamma$ [N]

The max. range in this case (e.g. loss of propulsion, thus emergency) is given by the type of aircraft and its load, the conditions of wind and weather and the altitude above ground.

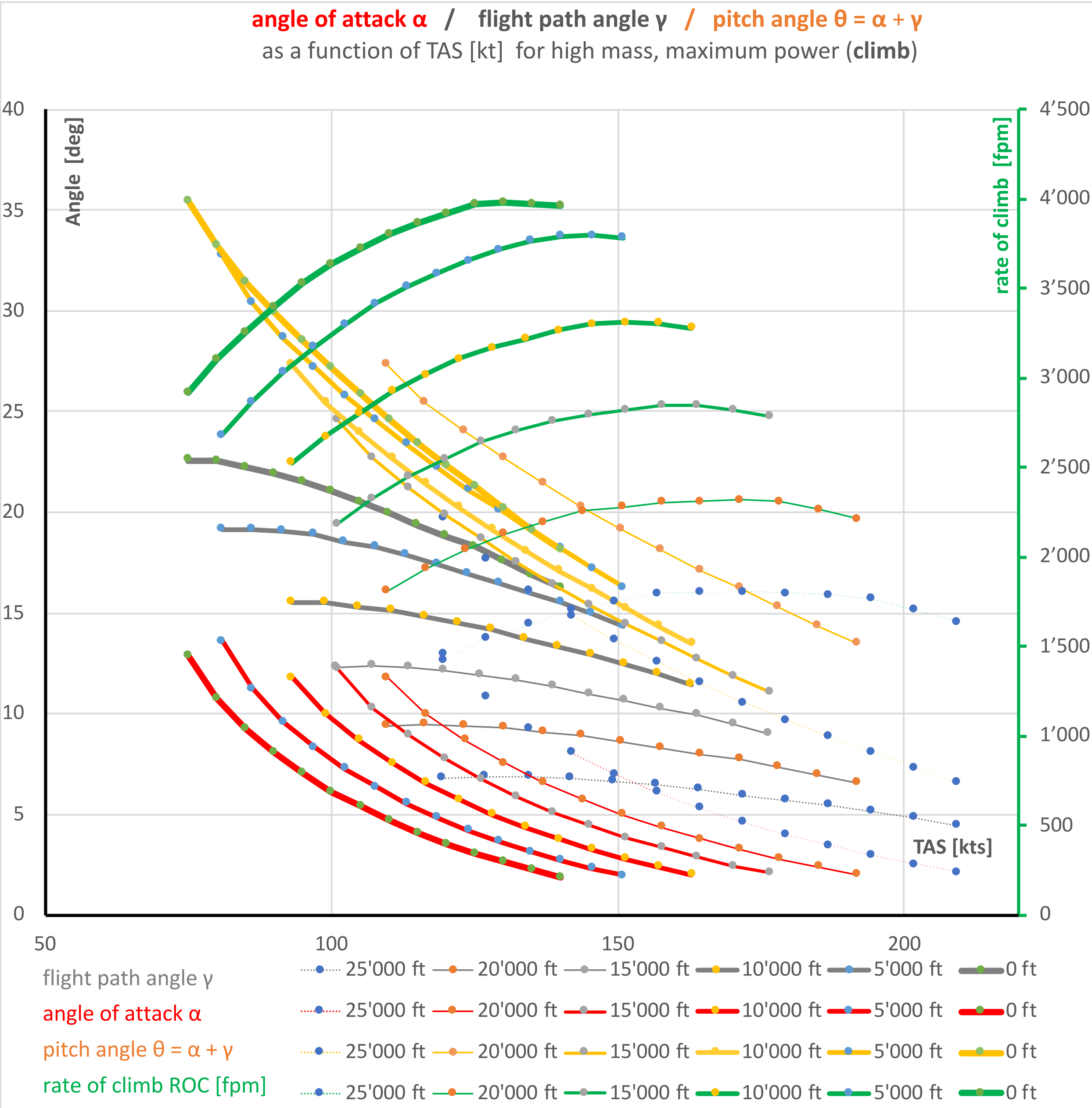
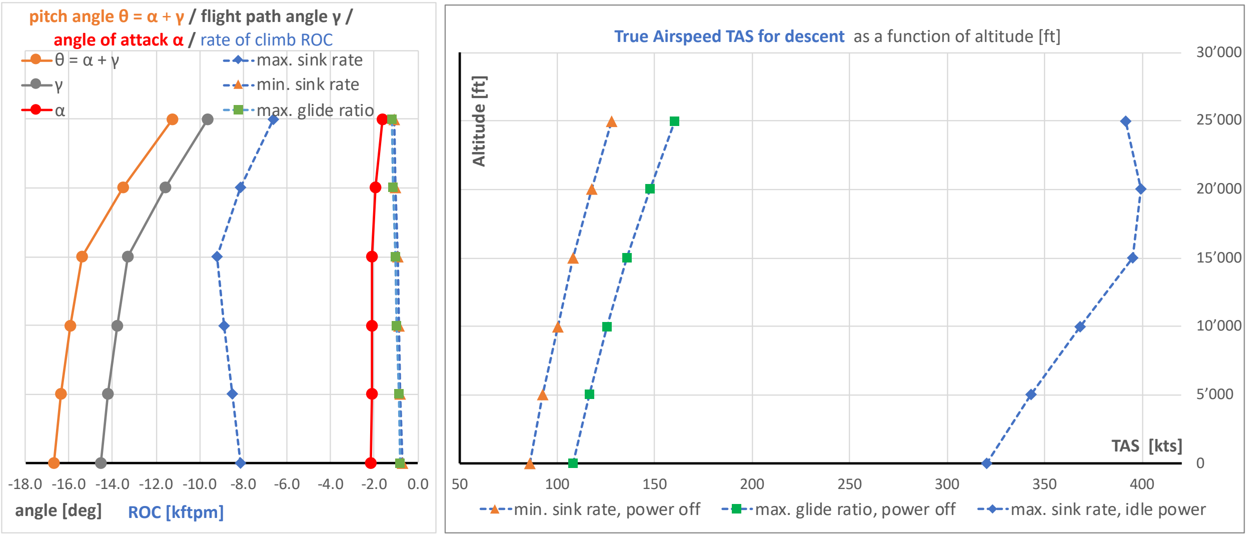


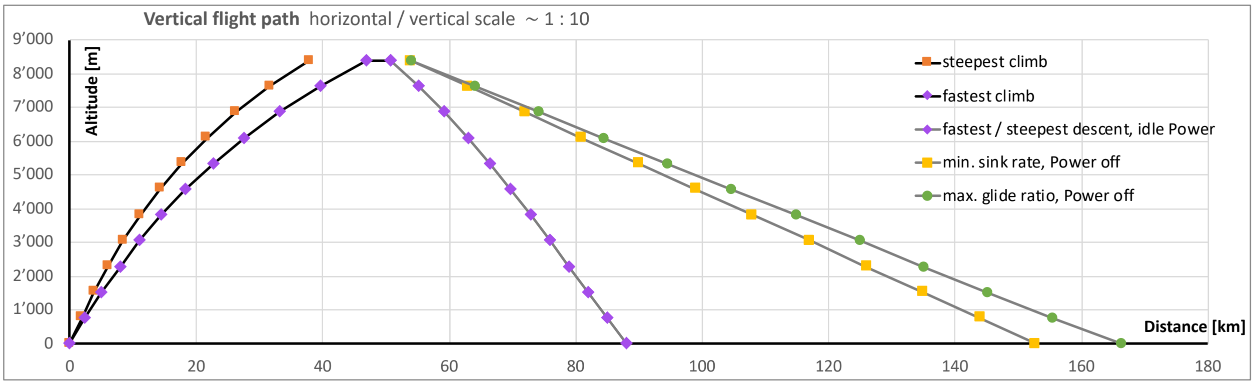
Fig. 10 Key parameters to determine climb as a function of true airspeed TAS for different altitudes: a.o.a. α; flight path angle γ; pitch angle θ; rate of climb RoC (from [6]).



Descent at max. sink rate: Angle of attack α; flight path angle γ; pitch angle θ = α + γ; rate of climb RoC for min. sink rate, max. sink rate and max. glide ratio.

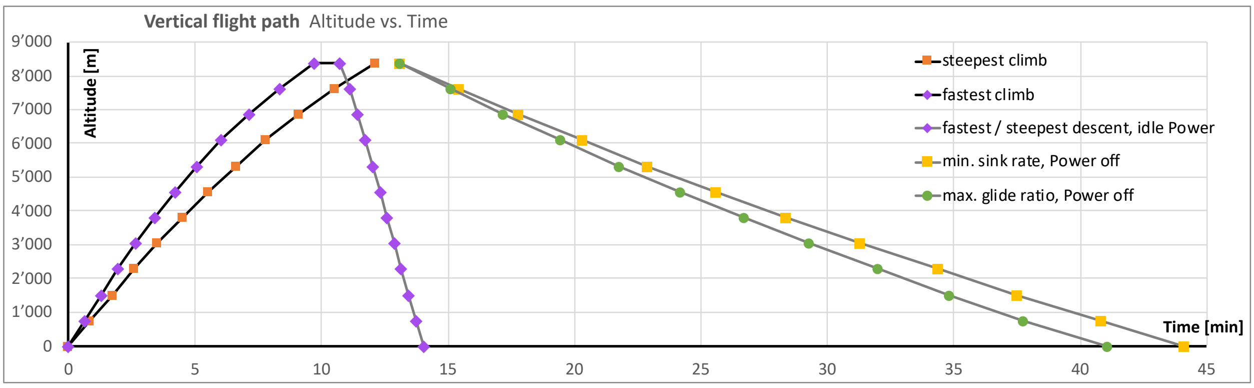
True airspeed TAS at different altitudes for max. sink rate (idle power) as well as min. sink rate and max. glide ratio (max. range) for power off).

Fig. 11 Key parameters to determine descent as a function of altitude (from [6]).



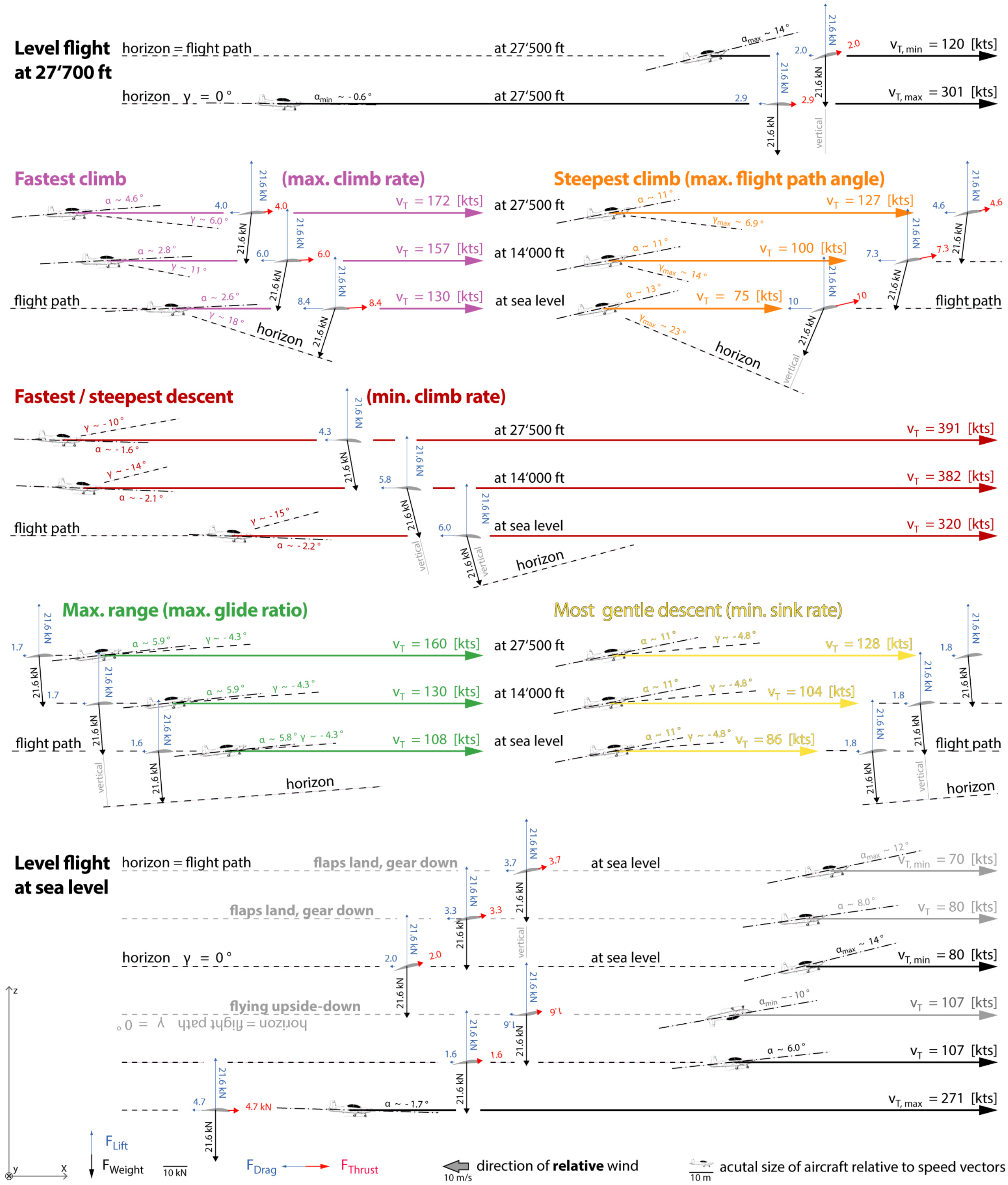
Note: The horizontal / vertical scale is ~1:5 and thus is tan γ (flight path angle).

The max. glide angle is ~2.5 times the max. climb angle.



Note: The max. rate of descent is about -2 times the max. rate of climb while the min. rate of descent is ~ 0.25 times the max. rate of climb.

Fig. 12 Vertical flight path extremes of a modern military trainer aircraft (from [6]): that is max. pitch angle, max. rate of climb, min. sink rate and max. glide glide ratio (max. range) for a) Horizontal and vertical distances; b) Time and vertical distance.



Note: The depicted a.o.a. values cover the whole range of possible angles of attack, that is from approach to climb and (high) speed cruise for a military trainer aircraft – including flying upside down.

F_{Thrust} is between 7 and 45 % of F_{Weight} and so is F_{Drag} of F_{Lift}.

TAS for fastest climb (max. climb rate) and for max. range (max. glide ratio) are almost identical

TAS and α for steepest climb (max. flight path angle) and for most gentle descent (min. sink rate) are ~ident.

The speed vectors are not to scale compared to Fig. 17 (example of speeds of a yacht) and the true wind is coming from the left for the sailcraft, but from the right for the aircraft.

Fig. 13: Balance of forces, true wind or true air speed, angle of attack α and flight path angle γ for typical states of operation and the vertical flight path from Fig. 10 to Fig. 12. All data for a modern military trainer aircraft (from [6]).

6. Balance of forces on sailcrafts

Overview

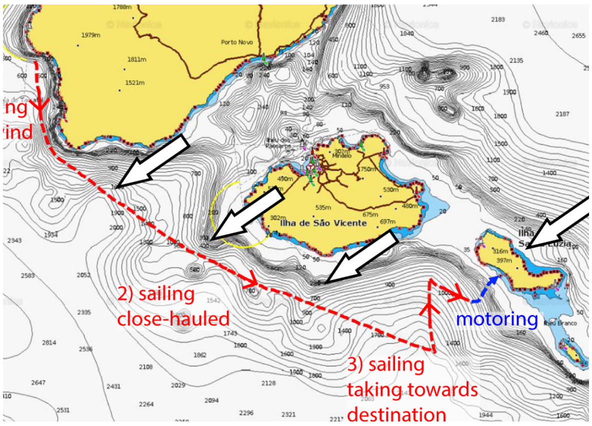
Sailcrafts can sail against or away from the wind. In the first case, lift forces on the sail propel the craft against the wind and the equivalent forces on the hull and keel keep the craft from simply being blown away (see par. 1, Fig. 1 and. Fig. 18, 19).

Courses of sailing

The course is defined by the direction of true wind and the destination point (see Fig. 14):

- against the wind (hauled or close-hauled): tacking/beating (short tacks)
- half-wind-course (reaching): long tacks, holding the same course relative to the wind
- with the wind (running): tacking/beating (short tacks)

Tacking/beating: for courses with or against the wind, it is necessary to repeatedly change the course.



1) Half-wind-course at the beginning; 2) Close-hauled-course during passage; 3) Tacking towards destination island. Note, that the last bit of the course is directly against the wind, thus sails have been taken down and the boat is propelled by a motor. See also paragraph 13, Fig. 35.

Fig. 14 Track of a sailing course (from [7]).

For both fleet and match racing, there are always parts of the course to be mastered against and with the wind, thus taking/beating is inevitable.

Sailing *against* the wind

Fig. 15 shows a head- and a mainsail with attached flow or air, indicated by the wind threads or tell-tales (note the similarity to the tell-tales on a gliders cabin roof from Fig. 6). The wind wane at the top of the mast indicates a low a.o.a., thus course is clause-hauled.

Fig. 15 Tell-tales on close-hauled courses:
a) Headsail (luff-side, lee-side is hidden)
b) Mainsail (at the leech).

Velocity made good (see Fig. 16) indicates how fast a boat sails *against* the true wind. It is a crucial value not only for both fleet and match racing (head to head, e.g. the America's Cup).

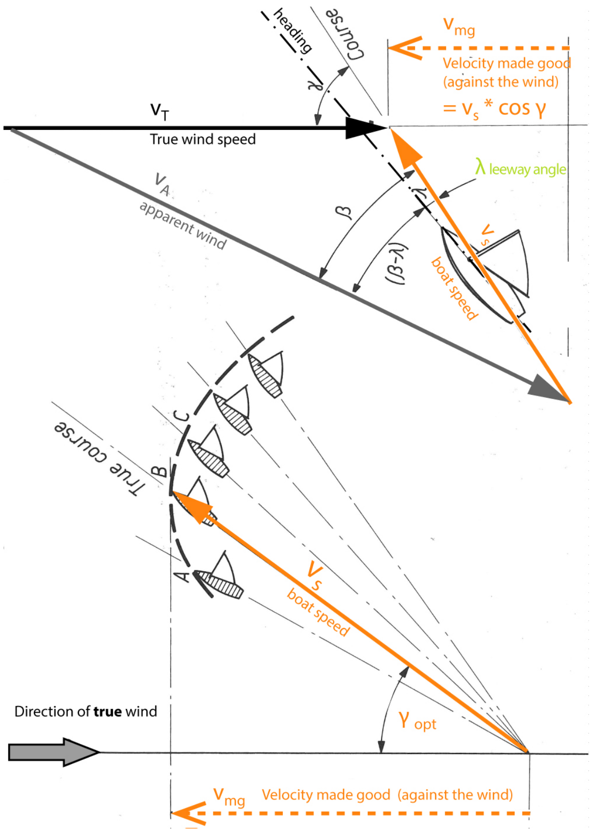


Fig. 16 Definition of v_{mg} = velocity made good (from [3], redacted for better legibility).

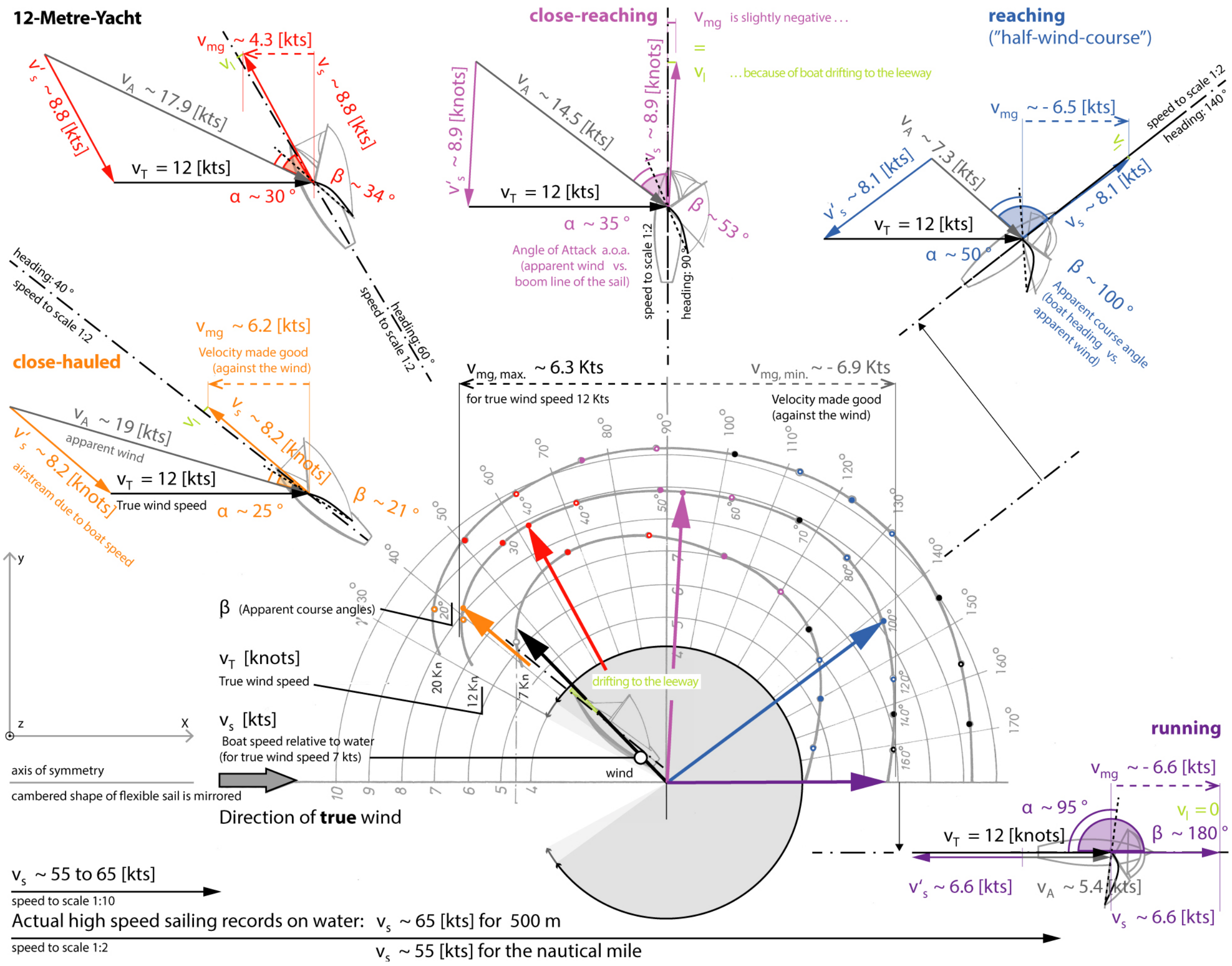
The driving force against the wind is the component of the lift force on the sail, that is heading against the direction of the apparent wind (see Fig. 17, 19). Sailing *directly* against the wind is impossible, because drag will always be higher than this component – no matter wether foils or wing sails are used.

To sail against the wind (close hauled or hauled), a high lift/drag ratio is needed. The airflow needs to be attached to both sides of the sail(s), just like to wings of an aircraft in stable flight conditions (see paragraph 3, Fig. 3, state 2).

Sailing with the wind

To sail half-wind or with the wind (reaching or running), the angle of attack α of the sail becomes much greater compared to sailing against the wind.

The airflow will therefore (partly) separate from the sail on the leesside and the proportion of drag forces propelling the boat becomes much greater (Fig 26).



Note: The speed vectors are not to scale compared to Fig.14 (example of speeds of a military trainer aircraft) and the true wind is coming from the left for the sailcraft, but from the right for the aircraft.

Fig. 17 Performance polar for speed of a 12-metre-yacht (from [5], redacted for better legibility).

Performance polars

Boat speed (relative to water) and the suitable angle of attack α of the relative wind to the boom of the sail both are a dependent on the following three parameters:

- True wind speed (given by the circumstances);
- Heading and apparent course angle (chosen).

They are depicted in performance polars (see Fig. 17 and paragraph 13).

Note that boat speeds are in a tight range for angles of attack α for properly trimmed and balanced boats, although the range of heading is ~ 310° against and with the wind (almost a full circle) and although the driving forces are either lift (close-hauled) or lift and drag (reaching or running).

3-dimensional balance of forces on sailcrafts

For sailcrafts it is impossible to draw a complete balance of forces in two dimensions only like shown in Fig. 1, 18 and 20: The aerodynamic forces on the sails and on the hull and keel are both in two different fluids and shifted in the third dimension (z, above and below the water surface).

Fig. 19 shows the two-dimensional balance for courses that cover the whole range in sailing from close-hauled (against the wind) to running (downwind) (as in Fig. 17 for speed). Fig. 20 shows the three-dimensional balance of forces and explains the polar diagram of forces for sailcrafts.

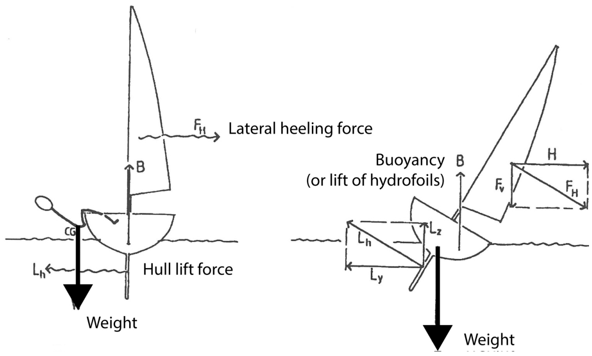
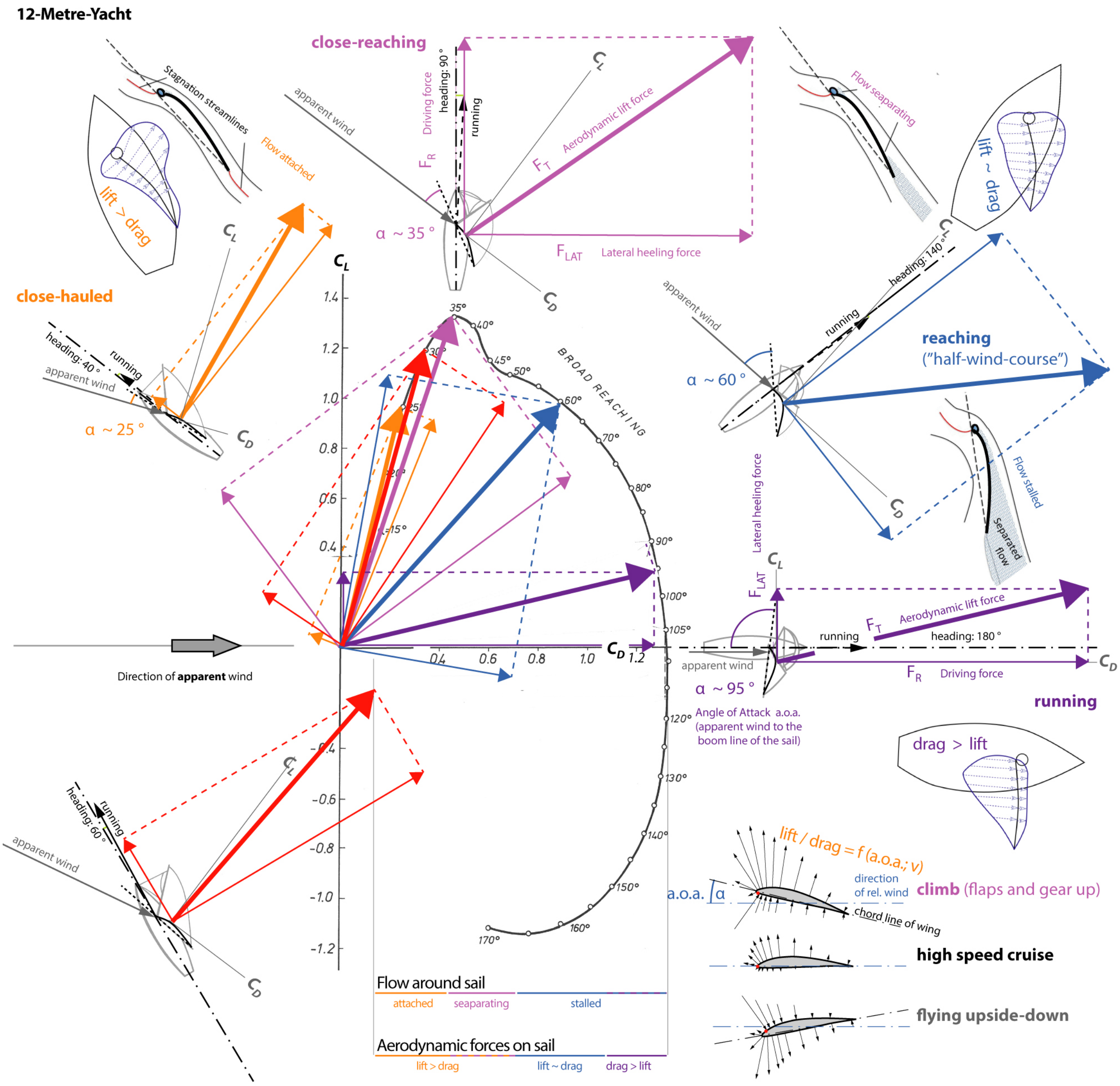


Fig. 18 Two-dimensional balance of forces on boats (x-z, from [2], redacted for better legibility).



Note the comparison of pressure fields around wings and sails: Aircrafts can only be operated at "close-hauled"-courses, that is more or less directly against the (relative) wind.

Fig. 19 Two-dimensional balance of forces on boats (from [5]), redacted for better legibility and complemented with flow field around sails (from [10]), pressure fields around sail (from 11]) and pressure fields around wings (from [4]) for better comprehensibility.

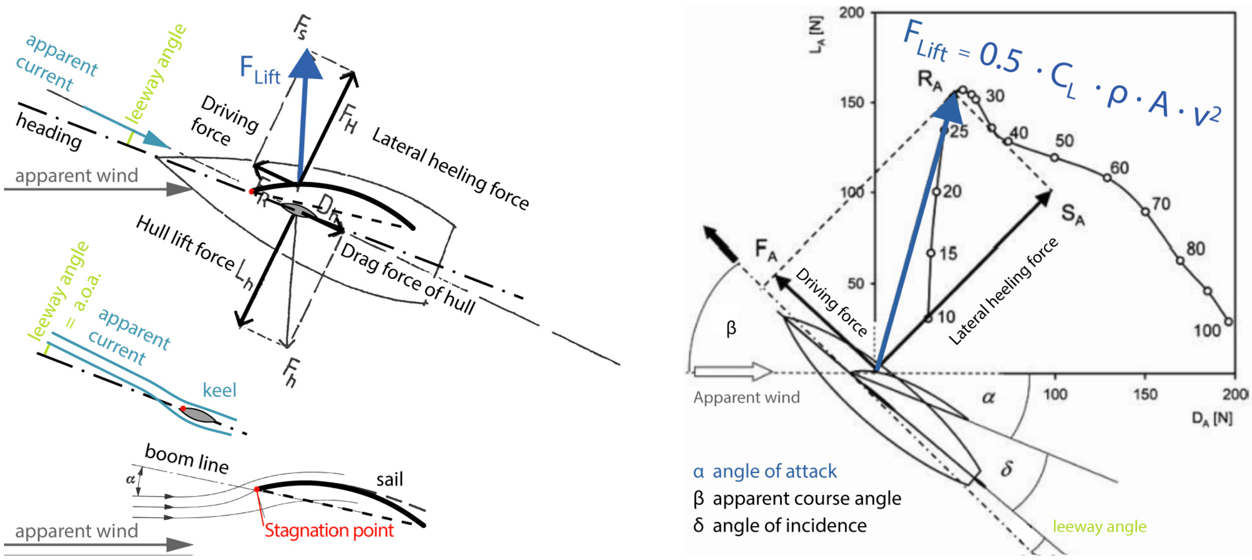


Fig. 20 a) Three-dimensional balance of forces on boats (x-y, from [2]), r. f. b. legib and complemented with flow of air around sail and current around keel (from [3] [5]) for better comprehensibility.
b) Polar diagram with 2-D balance of forces on sails (x-y, from [8], r. f. b. legib.).

Heaving to in case of heavy weather or storm

The most feared circumstances by sailors are heavy weather conditions with strong winds and high waves. To get the boat in a more or less stable state, the two sails (head and main) together with the rudder are used to create at balance of forces, so that the boat stands practically still: main sail is eased, jib (headsail) is backed (contrary to normal standing of the sail) and tiller is lashed to leeward, so that the rudder stand luffwards(see Fig. 21).

Heaving to is surprisingly peaceful and gives the sailor time to recover and get organised. However, the boat will still drift slowly to the leeway. Heaving to can be looked at as a self-stabilising mechanism and is therefore of special interest from a control systems engineering point of view.

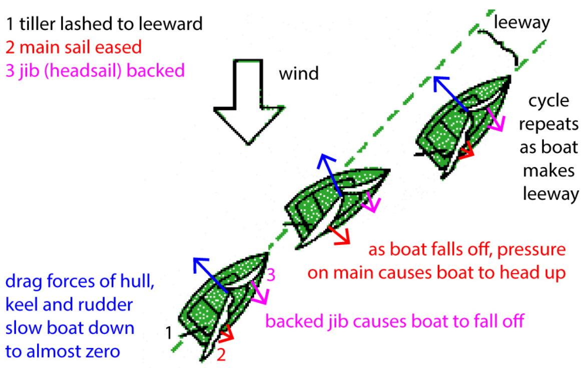


Fig. 21 Heaving to: A repeating cycle of heading up and falling off with a resulting, slow movement to the leeway (from [9], redacted for better legibility).

The max. range in this case is given by the next coast in the direction of the wind. This is why sailors try to stay away from the leeward coastline as far as possible in case of threatening storms.

Note that, while for aircraft the loss of propulsion can pose a serious threat, for sailcraft the controlled eliminiation of the propulsion by the wind is a way to cope with the threat of the enormous forces of the elements.

7. Parameters to increase lift

To increase lift, the overall deflection of the airstream or current is the principal parameter to aim for:

- Better attachement of the airflow;
- Higher (possible) angle of attack α;
- Higher velocity of the wind relative to the wing or foil (especially on the leesside).

The camber of the wing and the angle of incidence / mounting angle σ are fixed for aircraft, but flexible for sailcraft. The combination of a.o.a. α + camber is a result of easing or trimming the sail(s).

To compare sails and wings in regard of increasing lift, one could say:

- The headsail is to the mainsail what the slat is to the wing;
- The combination of all flexible parts of the sails (angle of incidence σ and camber) is comparable to the effect of flaps on wings and the angle of attack α of the wing (of course!).

This is in a simplified manner (see Fig. 22 to 25).

Slats and flaps added to wings

Slats and flaps allow higher a.o.a. and therefore higher lift forces on wings (see Fig. 22 and 23):

- Slats act as anti-stalling devices, their addition to the wing results in higher stall angle $C_{L,max}$.
- Flaps increase the overall camber of the wing, their addition to the wing results in higher $C_{L,0}$ and $C_{L,max}$ and in higher drag.

A greater camber of the wing results both in (slightly) higher lift and drag (as a basic design decision).

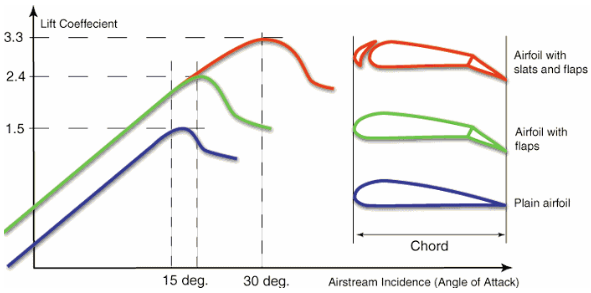


Fig. 22 Effects of slats and flaps on C_L as a function of the angle of attack α (from [12]).

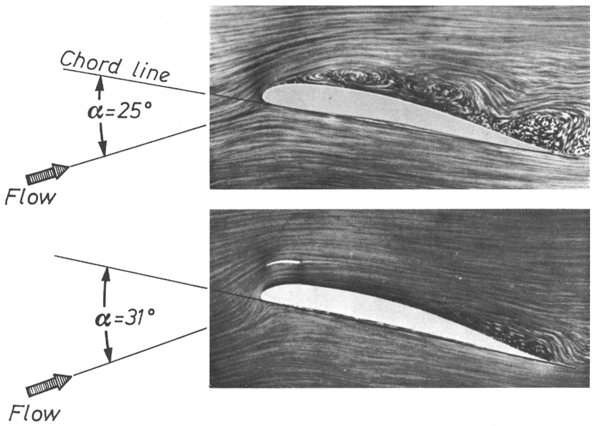


Fig. 23 Slats are powerful anti-stalling devices [5].

Combination of sails and trimming

The combination of headsail (jib or genoa) and mainsail results in significantly higher lift:

- The stagnation point of the headseal is moved towards the windward side of the sail because of the upwash ahead of the mainsail. The headsail therefore will thus be driven more cambered (at a higher a.o.a.) and produces more lift (see Fig. 24).
- Between the two sails, a high speed flow region is created with the effect of higher flow velocity on the entire lee surface of the headsail and higher lift forces (see Fig. 25).
- The combination of angle of attack α and the camber is chosen, so that the luff points towards the apparent wind and thus the flow of air is attached on both sides of the sail, depending on the true (and therefore the apparent!) wind speed (see Fig. 3, 4 and 17).

(see Fig. 24 and 25)

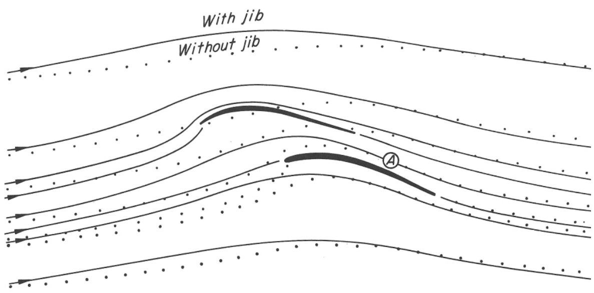


Fig. 24 Airflow around mainsail with/without jib with the high speed region A (from [5]).

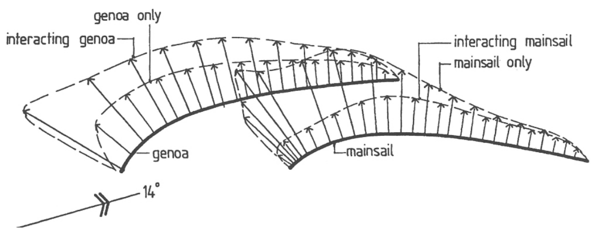


Fig. 25 The forces on the sails are determined by the differences in pressure on each side of the sail. The two interacting sails produce both higher pressure differences and thus lift forces (from [5]).

Primary and secondary parameters for lift/drag

The parameters with the biggest impact on lift and drag are the angle of attack and the velocity or speed – and for sailcraft the camber of the sail as well, depending on the course relative to the true wind.

aircraft	sailcraft
lift/drag ° = f (a.o.a.; v)	lift/drag = f (a.o.a.; camber)
lift/drag ° = f (camber)	lift/drag = f (v)

° due to the pressure field around wing or foil

A secondary parameter for aircraft is the camber of the wing (as a design decision) and for sailcraft it is the wind speed (as a natural boundary condition).

8. Conclusion

The direct experience of air flows and pressure (e.g. when trimming and heeling) and their use for driving a sailcraft may lead to a better understanding of aero- and hydrodynamic forces and their proper handling for any application of lift (and drag) like flying, diving, foiling, surfing, kiting and sailing.

Thus, one may conclude: Go sailing! Go surfing! It's cheap, it's good fun and it broadens the horizon in every sense (and: your licence will never expire . . .).

The headsail helps to keep the flow of air attached to the lee-side of the mainsail. Therefore significantly more lift is generated to propel the boat ~perpendicular to the true wind.

Fig. 26 Sail twist of a classic boat reaching (on half-wind course, from [13]).

Further discussions could get more precise about flow of fluids, pressure fields and forces, e.g.

- The moment for thrust (when the engines' thrust does not meet the centre of gravity of the aircraft); choice of flight route due to wind and weather conditions, jetstream etc.
- About acceleration and starting vortices,
- Drag due to heeling

or about a wider range of applications like foiling and planning of sailboats, submarines, keel design etc. – or about mathematical methods to iteratively calculate forces on wings etc. etc.

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10. Glossary of selected terms for sailing

to beat / tack	kreuzen, d.h. wiederholte Richtungswechsel relativ zum Wind
close hauled	Kurs hart am Wind (gegen den Wind)
current	Wasserstrom
genoa	Genua (mittelgrosses Vorsegel)
headsail	Vorsegel: Fock, Genua, Gennaker, Spinnaker u.a.
heaving to	Beidrehen
heeling	Krängung: Neigung zur Seite
hull	Rumpf
jib	Fock (kleines Vorsegel)
to jibe	halsen, d.h. Richtungswechsel vor dem Wind
keel	Kiel
lee, leewards	Lee, facing away from the wind
luff, luffwards	Luv, towards the wind
luff	Vorliek, Vorderkante eines Segels
leech	Achterliek, Hinterkante eines Segels
reaching	Raumwindkurs (vor dem Wind)
rudder	Ruder
running	Vorwindkurs (direkt vor dem Wind)
tack	Schlag
to tack	wenden, d.h. Richtungswechsel gegen den Wind
tell tales	Windfäden
tiller	Pinne, d.h. Hebel zur Bedienung des Ruders
wind wane	Spion, d.h. Windzeiger für scheinbaren Wind

See aboutsailing.de for further terms.

11. Selected Effects on principal parameters

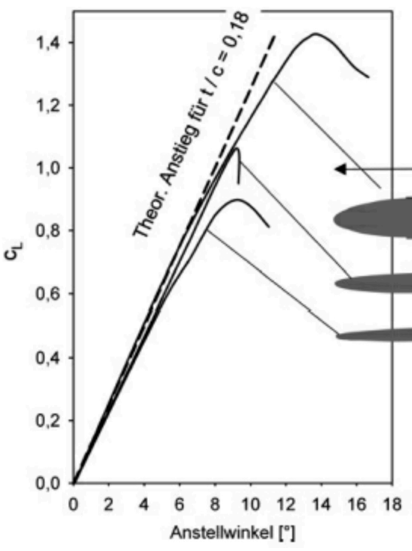


Fig. 27 Effect of camber of wing on $C_{L,\,max}$ as a function the a.o.a. (from [8]).

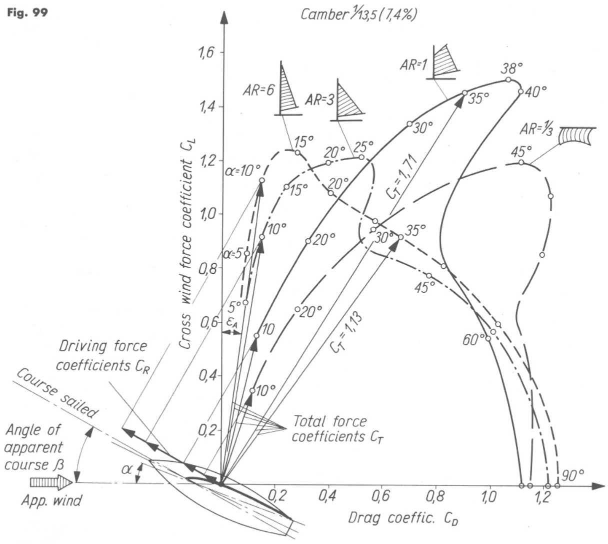


Fig. 28 Sail polars for four sails of the same camber (1/13.5 = 7.4 %), but different planform (aspect ratio). Note conspicuous differences in the total aerodynamic force when foils operate at the same a.o.a. (from [5]).

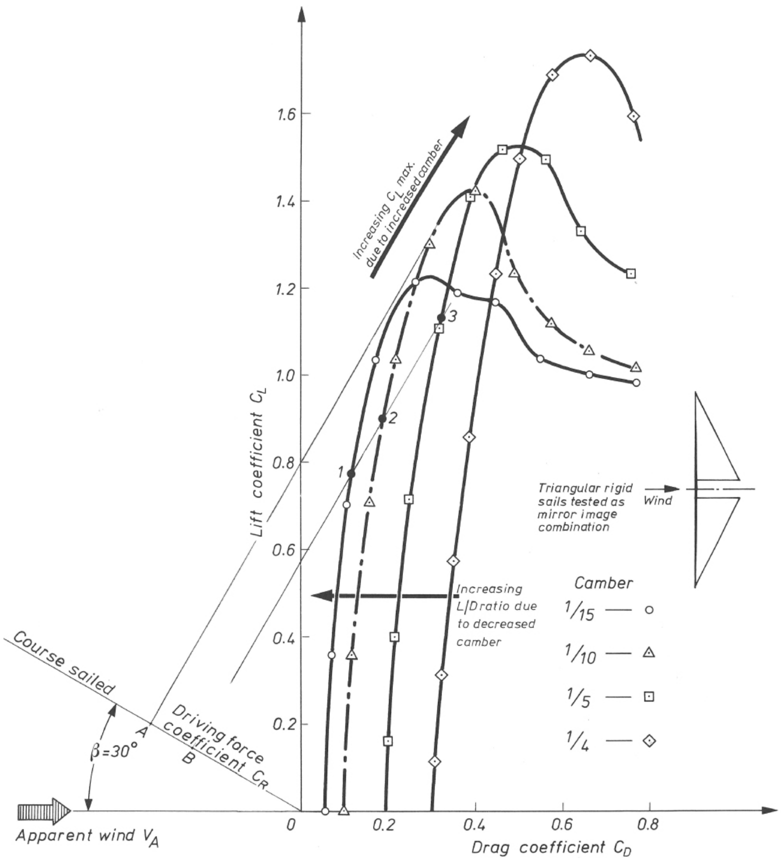


Fig. 29 Effect of camber of sails on L/D ratio and $C_{L,\,max}$ and C_D (from [5f]).

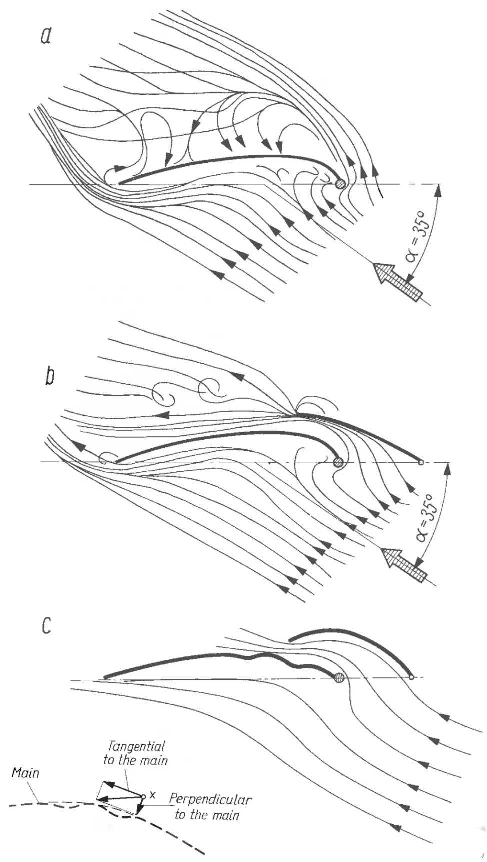


Fig. 30 Effect of the combination of head- and mainsail on flow of air. (from [3]).

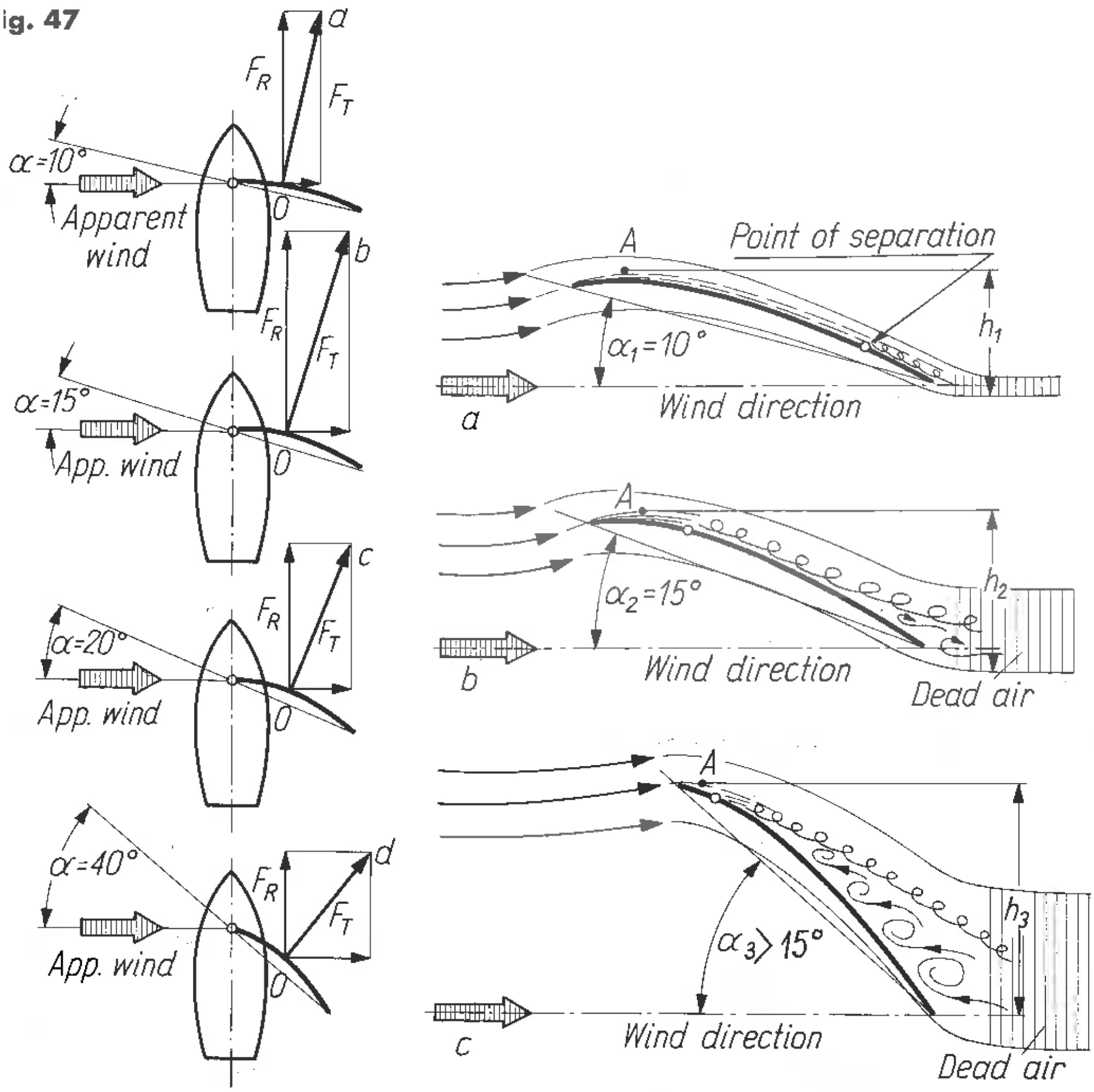
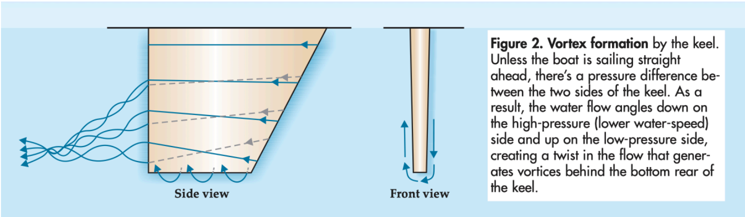


Fig. 31 Effect of a.o.a on flow or air: attached, separating, stalled (from [3]).

12. Vortices formation by the keel and the sailtop



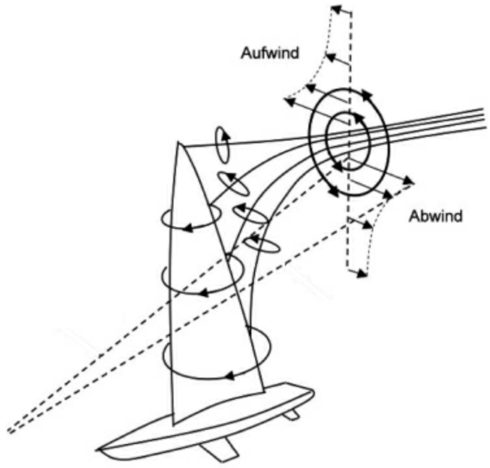


Fig. 32 Vortex formation a) by the keel (from [14]). b) by the sailtop (from [3] and [8]).

Fig. 33 Sailtops form vortices visible in fog. Volvo Ocean Race 2001–02 off Cape Town, South Africa. (Photo copyright Daniel Forster) from [14]).

13. *Polar diagram for forces on sails / Coefficients of lift and drag*

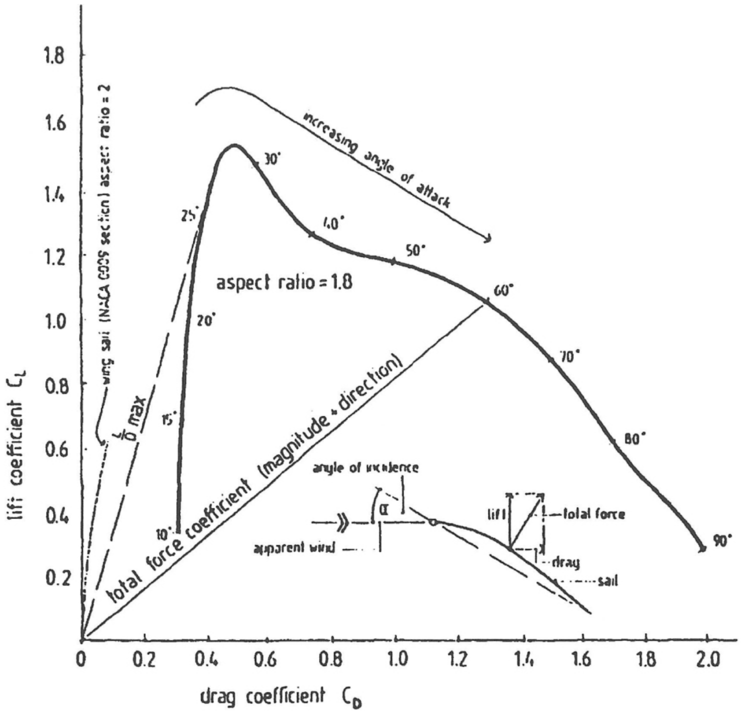
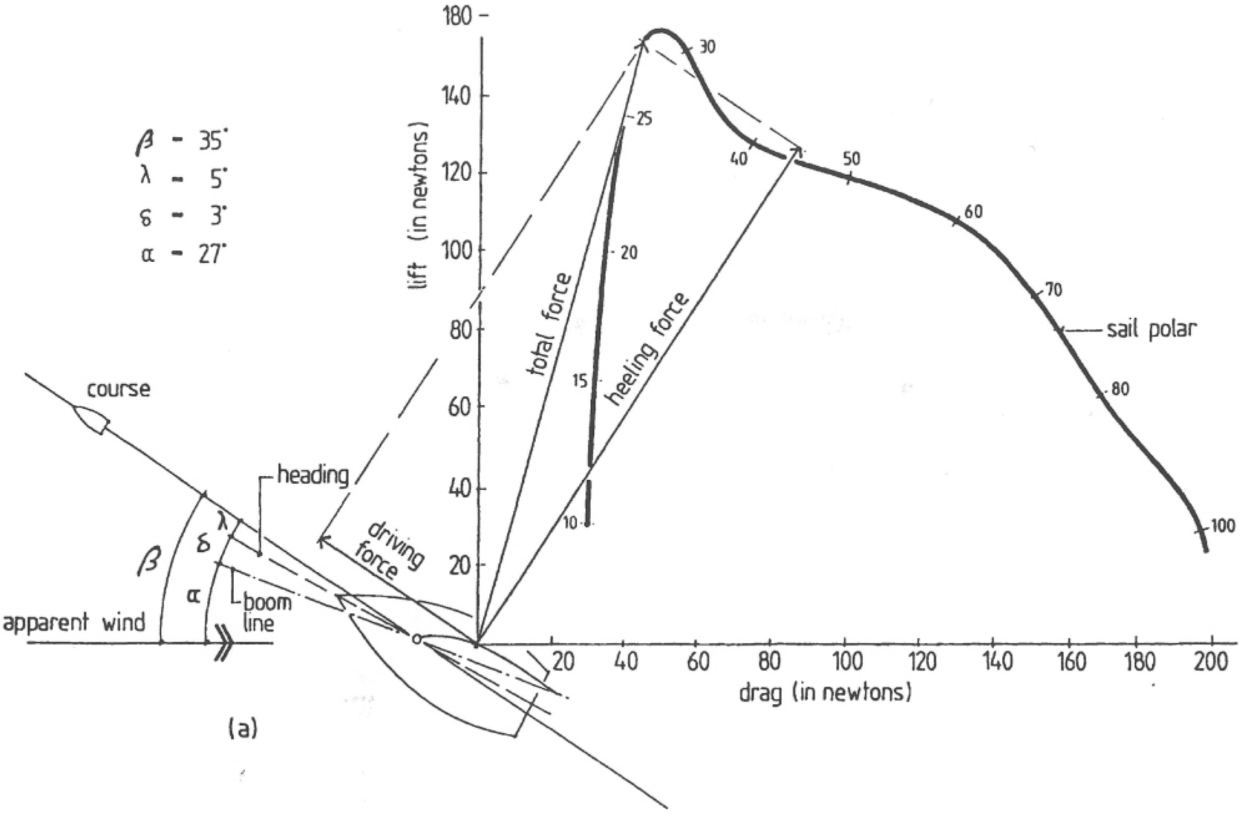


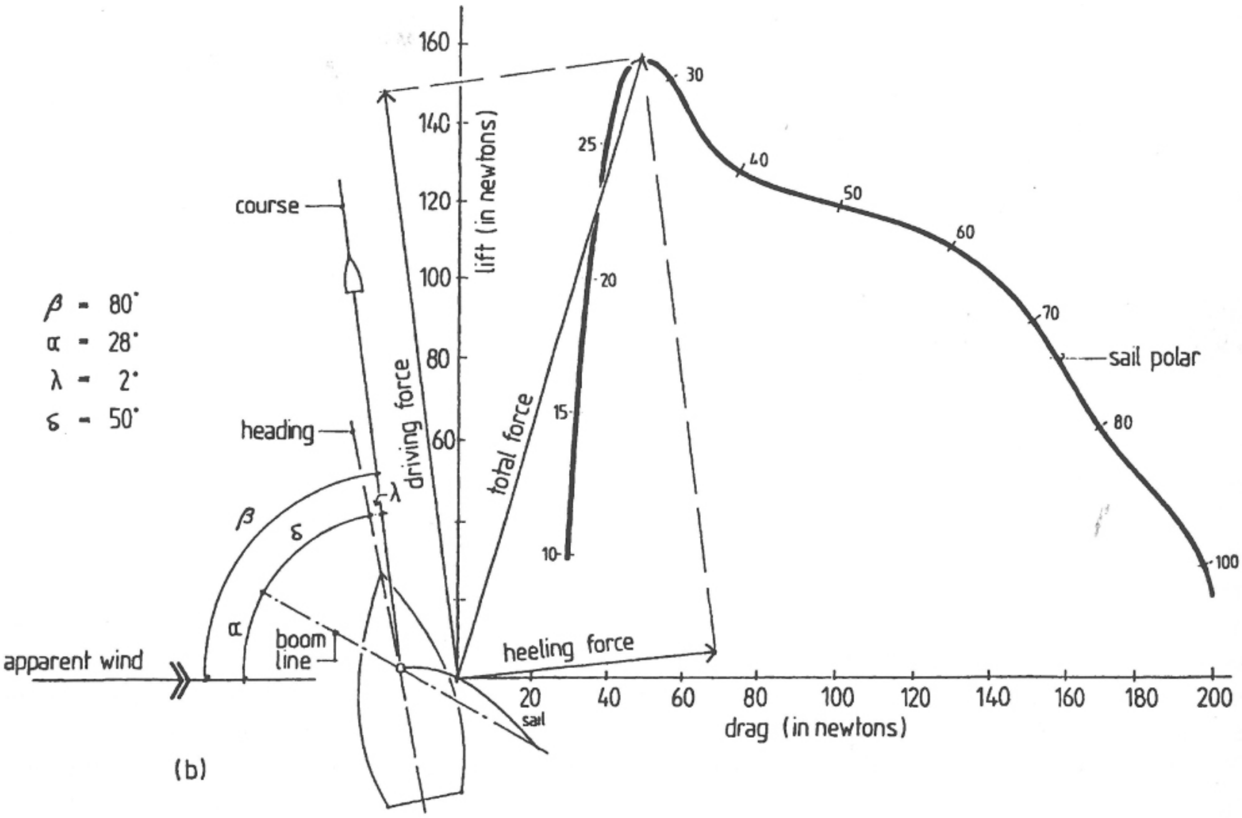
Fig. 3.26 **A 'polar diagram' for the mainsail alone of a 3.7 m centreboard boat. The measurement was made in actual winds on a full scale boat by determining the forces in a tethering line to a fixed mooring. C_L and C_D are the measured lift and drag coefficients which are related to the actual lift and drag forces as explained in the text. The numbers along the curve refer to the angle of incidence or attack of the apparent wind on the sail. Although the sail had some twist, the angle of attack was measured between the direction of the apparent wind and the boom. The dashed line tangent to the curve from the origin gives the angle of attack for which the lift/drag ratio is a maximum, in this case about 26°. The dotted curve is that of a symmetric section wingsail of similar aspect ratio. No hull or rigging drag is included in this curve which is why the sail measurement made under realistic conditions is pushed so far to the right along the drag axis. The arrow marked total force coefficient determines the magnitude and direction of the force on the sail when the angle of incidence is 60°. In this case the direction of the force is at about 40° to the apparent wind direction.**

Fig. 34 Polar diagrams for forces on sails (from [5]).



β - 35°
λ - 5°
δ - 3°
α - 27°
lift (in newtons)
drag (in newtons)
course
heading
boom line
apparent wind
driving force
total force
heeling force
sail polar

(a)



β - 80°
α - 28°
λ - 2°
δ - 50°
lift (in newtons)
drag (in newtons)
course
heading
boom line
apparent wind
driving force
total force
heeling force
sail polar
sail

(b)

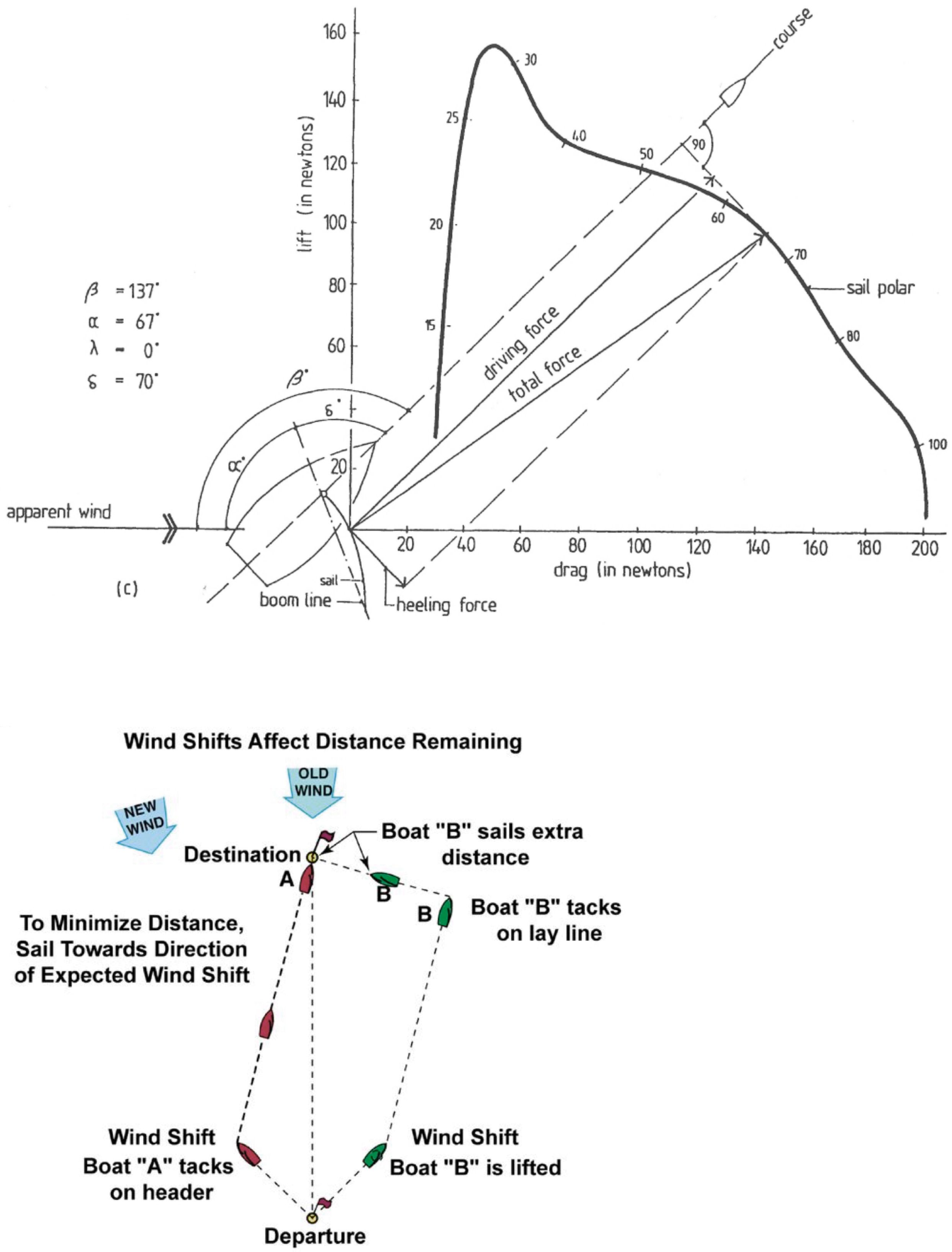


Fig. 35 Sailing against the wind: choice of course in expectation of a wind shift.

14. *Coefficient of lift when flying upside down*

CAN AN AIRFOIL PRODUCE LIFT WHEN IT IS FLYING UPSIDE DOWN?

- NACA 2415 AIRFOIL
- Zero-lift α, $\alpha_{L=0} = -2°$
  - So airfoil will generate positive lift (when right side up) for $\alpha > -2°$
- Now turn airfoil upside down
  - If $\alpha = 0°$, negative lift
  - If $\alpha = 2°$, zero lift
  - If α is greater than 2° (but reading $-\alpha$ range) airfoil will generate lift in positive vertical direction
- Upside down airfoil at same α generates less lift
- Example:
  - Right side up: $\alpha = 10°$, $c_l = 1.2$
  - Upside down: $\alpha = 10°$, $c_l = -0.8$

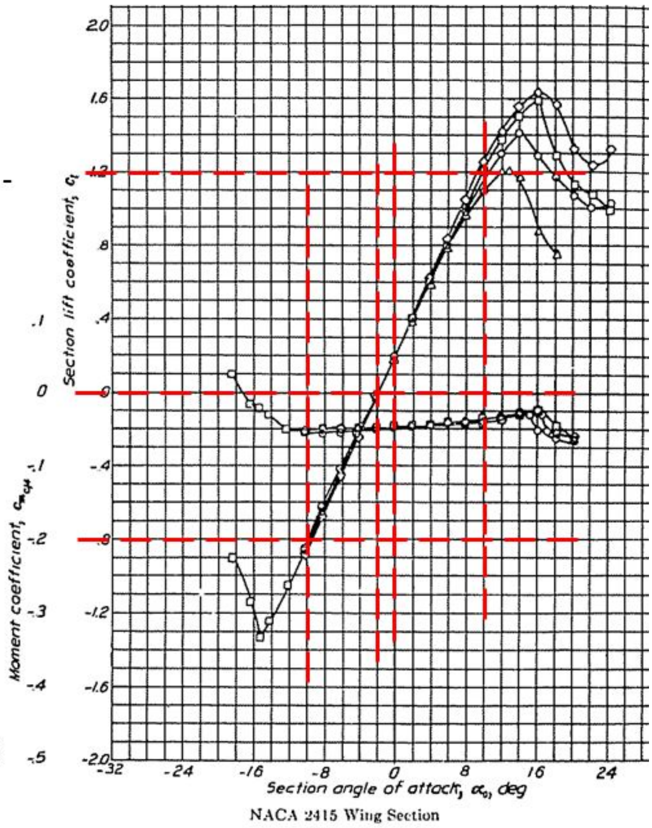


Fig. 36 Example of C_L as a function of a.o.a from negative to positive stall for NACA 2415 (from [15]).

15. *Pioneering hydrofoil sailing/kite boats*

Fig. 37 Four examples of pioneering hydrofoil sailing/kite boats: (a) Gordon Baker, Monitor (1955); J Walker's Planesail: developed by a group of ex aircraft-engineers, who claimed to have completely rethought the concept of the "soft cloth and wet strings sailing boat", the small trailing foil controls the angle of incidence σ of the four rigid driving foils; (c) James Grogono, Icarus (1972); (d) Jacob's ladder (1978) (a, c and d from [16], b from [5]).

16. *Actual cross-border design*

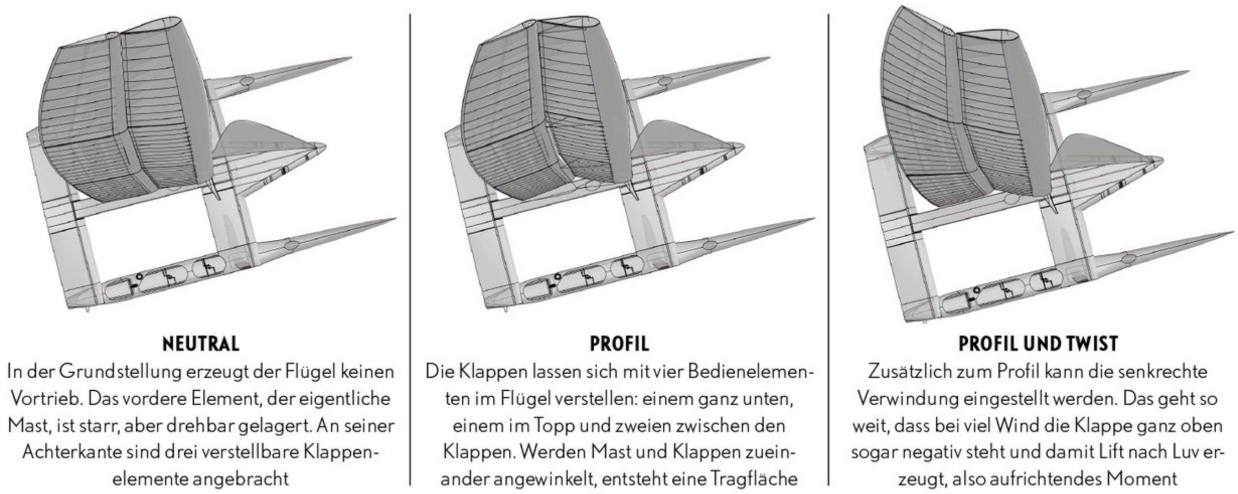


Fig. 38 Three states of operation of the main wing of the America's Cup boat (from [17]).

Fig. 39 Hydrofoil sailing boats: (a) International Moth class (2004); (b) America's Cup (2013) (from [16]).

17. A Passively Morphing Trailing Edge Concept for Sailing hydrofoils (from [16])

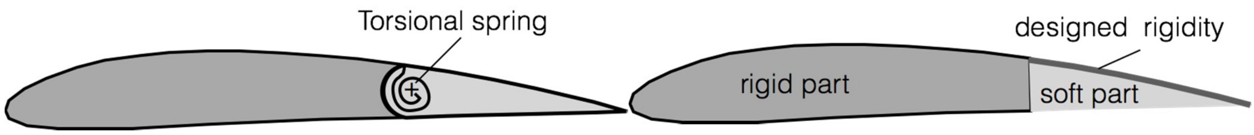


*Fig. 25: Passive flap: (**a**) Torsional spring concept; (**b**) Flexible trailing edge concept (2013).*

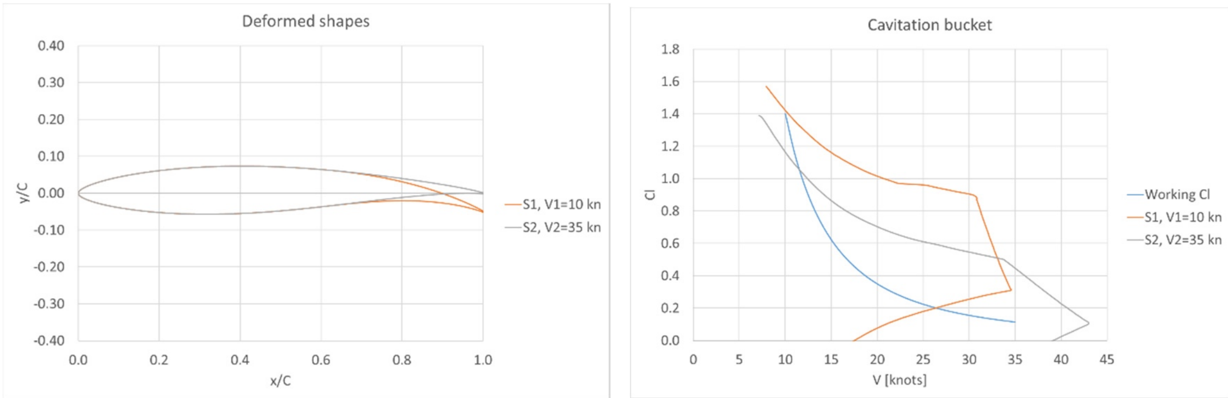


Fig. 39 Deformable airfoil: (a) wing section at take-off speed and at maximum speed; (b) Lift coefficient of the two sections as a function of the operating speed.

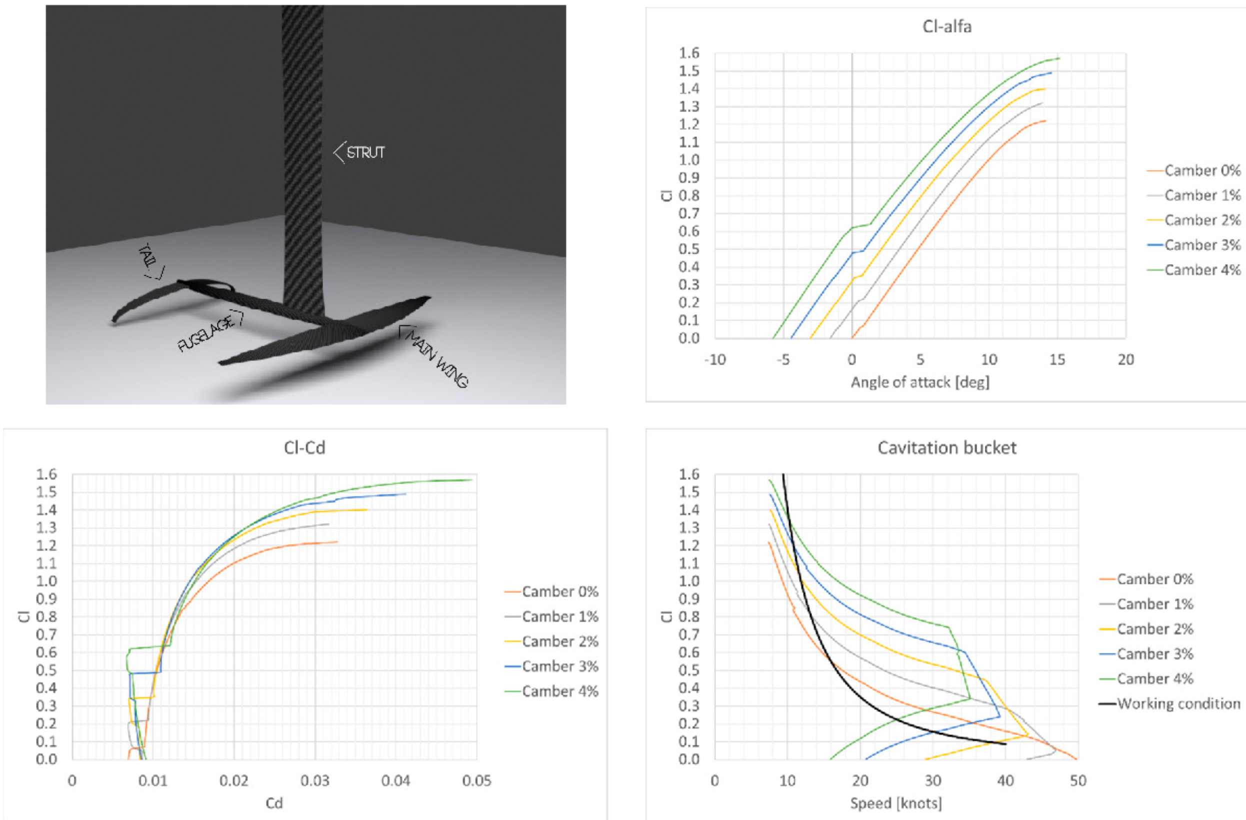


Fig. 40 Hydrofoil characteristics: (a) schematic assembly of a kite-board hydrofoil; (b) lift coefficient of the wing as a function of the angle of attach and for different camber values; (c) polar curves (lift coefficient versus drag coefficient for different camber values); (d) working condition line superimposed to the lift coefficient of the wing as a function of the speed considering also the lift limitation due to cavitation.